論文の内容の要旨

Interacting boson model from energy density functionals
(エネルギー密度汎関数に基づいた相互作用するボソン模型)

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Among many other finite quantal systems, the atomic nucleus takes on a unique and stunning collective aspect characterized by the remarkable regularity of its energy spectra. The most simple, yet essential collective motion is of quadrupole type, where the equilibrium shape of a nucleus can be a spherical vibrator, an ellipsoidal deformed rotor and an object in between, depending on the number of protons and/or neutrons. Deformation occurs as a consequence of the spontaneous symmetry breaking of the nuclear mean field, and the rotational motion manifests itself as a realization of symmetry-restoration mechanism, which is a general concept in physics. Therefore, understanding the quadrupole collective dynamics from a microscopic perspective has always been an intriguing subject in nuclear many-body physics. Thanks to the developments in experimental techniques, it has nowadays become possible to study various collective modes of excitation in medium-heavy and heavy nuclei.

Self-consistent mean-field theory with a given microscopic energy density functional (EDF), such as Skyrme, Gogny and other interactions in relativistic regimes, has provided both universal and accurate description of bulk properties of finite nuclei over almost entire chart of nuclides, including mass, intrinsic deformation, and giant resonances, etc. To obtain the spectroscopic observables, however, one should go beyond the mean-field approximation to take quadrupole correlations into account and to restore the broken symmetries. A number of studies have been done rigorously in terms of the configuration mixing and/or the restoration of broken symmetries, but are computationally demanding and much involved particularly when the triaxial degrees of freedom enter. Alternatively, phenomenological study within the interacting boson model (IBM) of Arima and Iachello has witnessed enormous success in reproducing the low-lying structure of medium-heavy and heavy nuclei. While the IBM reflects a certain microscopic picture associated with the underlying many-fermionic dynamics, the problem concerning how this model is justified for general cases of quadrupole collective states has remained an open question.

We have proposed a novel way of deriving a Hamiltonian of the IBM from microscopic self-consistent mean-field theory. The IBM in this context refers to the proton-neutron IBM (IBM-2), which distinguishes the proton and the neutron degrees of freedom. Since a nucleus is comprised of protons and neutrons, we discuss the IBM-2 throughout, which reflects a microscopic picture much better than the simpler version of the IBM. The constrained mean-field calculation with a fixed EDF provides energy landscape, i.e., the potential energy surface for the quadrupole collective dynamics, which is subsequently mapped onto the corresponding classical limit of the boson Hamiltonian with respect to the boson coherent state. This mapping process yields strength parameters of the IBM Hamiltonian, thereby allowing to analyze the energies and the wave functions of excited states with good quantum numbers in the laboratory frame, and the quantum fluctuation that is missing in the mean-field approximation. The methodology is so general that it can be applied to all situations of the quadrupole collective states in principle, including those of heavy exotic nuclei. The initial work was published in Ref. [1], addressing the *proof of principle*. Subsequently, the validity of the methodology was further addressed in Ref. [2], introducing an unambiguous way of deriving the IBM Hamiltonian with the help of wavelet transform, and was applied to the systematic spectroscopic analyses of medium-heavy nuclei.

At the microscopic level, the IBM has its own long-lasting problem of not being able to describe the moment of inertia of rotational band when applied to well-deformed nuclei. We have shown how the IBM can be justified for the description of axially symmetric, strongly-deformed nuclei from the successful density functional approach [3]. In the deformed nuclei, the way that the nucleon system responds to the rotational cranking is shown to be substantially different from the one for the corresponding boson system. To remedy this deviation between deformed nucleon and boson systems, we proposed to introduce a rotational kinetic term in the boson Hamiltonian, and derived its coupling constant so that the rotational response of the boson system becomes identical to that of the nucleon system. As a consequence, the rotational bands of strongly-deformed rare-earth and actinoid nuclei are reproduced to almost perfect precision, without any adjustment of the excitation energies. Furthermore, this study sheds lights upon, and provides one with a crucial piece of information about the critical comment, which was made in the past by Bohr and Mottelson from a microscopic theory, as to the validity of the IBM for deformed nuclei.

Intriguing collective phenomena are also seen in medium-heavy nuclei in which the triaxial degrees of freedom needs to be included. The concept of the quantum phase transition (QPT), as well as the critical-point symmetry, serves as a paradigm for elucidating the complex nuclear structural evolution as function of nucleon number, and has been a subject tested by various microscopic perspectives. By employing the procedure of Ref. [1], a number of spectroscopic studies have been carried out [2,4,5,6,7] for those nuclei in many of which triaxiality plays an important role. Typical shape transitions between nearly spherical and weakly deformed γ-unstable nuclei in the mass regions $A \approx 100 \sim 130$ were reproduced using the Skyrme EDF in Ref. [2], while evidence for E(5) critical-point symmetry for some Ba and Ru isotopes was addressed there. Moreover, it was suggested in Ref. [2] that a large number of γ-soft O(6) nuclei may be observed in the right-lower quadrant of the doubly-magic nucleus ^{208}Pb, which should be examined experimentally in the future. The heavy nuclei around the mass $A \approx 190$ exhibit competition between prolate and oblate intrinsic states, resulting in a spectacular shape coexistence as observed experimentally. We have studied the spectroscopic systematics of these nuclei based on the IBM Hamiltonian derived from finite-range Gogny EDF [4,5,6]. Particularly we discussed the possibility of the coexistence of prolate and oblate shapes in Pt isotopes, and suggested that a single configuration, without introducing the intruder configuration of cross-shell excitation, is sufficiently well for Pt nuclei. We further predicted, prior to a measurement, the transition from prolate to oblate shapes in heavy Os and W nuclei as a function of neutron number N and the transition points $N = 116$. Along this line, we gave the first theoretical explanation on the γ-ray spectroscopy of neutron-rich Kr isotopes, carried out at the REX-ISOLDE facility at CERN [7]. Contrary to some earlier measurements, we concluded from both theoretical and experimental viewpoints that the shape evolution in the considered Kr nuclei occurs quite slowly, and that no sudden onset of deformation is observed. This result certainly has a significant impact, because the neutron-rich nuclei with mass $A \approx 100$, including the Kr isotopes, represent an intersection of collective and single-particle degrees of freedom, and also should be of common interest for the studies of shell structure, QPT, mass measurement and astrophysical processes.

All these findings are robust such that they are almost independent of the particular choice and the details of the EDFs used. This was further tested and confirmed by comparing the spectra, as well as the transition rates between the excited states, generated by the IBM Hamiltonian based on the EDF in relativistic mean-field (RMF) model with those by the geometrical five-dimensional collective Hamiltonian derived from the same RMF interaction [8]. In addition, peculiar features inherent to these two collective models are compared in detail, by which their current limitations and possible ways of improvements are suggested.

One of the important consequences of these analyses concerns the issue of the regularity in the level structure of non-axial (γ-soft) nuclei. The non-axial nuclei have been studied based on the two conflicting physical pictures: the rigid-triaxial and the γ-unstable rotor models. Since vast majority of the observed non-axial nuclei fall exactly in between the two geometrical models, the relation between the two has been of intriguing subject. In the IBM framework, the non-axial nuclei are described only by the O(6) dynamical symmetry, which is nothing but a realization of the γ-unstable rotor picture. Any IBM Hamiltonian composed of only up to two-body terms can never reproduce the level structure of non-axially symmetric nuclei, partly because the two-body Hamiltonian does not reproduce a stable triaxial minimum which is however seen in microscopic energy surface. We then proposed to introduce, for the first time, an essential three-body boson term in the proton-neutron IBM so as to reflect the microscopic calculation [9]. With such suitably chosen boson Hamiltonian, we have demonstrated that the above-mentioned empirical feature of non-axial nuclei can be explained naturally and that the finding resulting from this study is independent of the type of the EDFs used [9].

Finally, the nuclear structural evolution is analyzed through the ground-state properties, in which the quantum fluctuation (correlation) is included by the diagonalization of the boson Hamiltonian formulated by an EDF. The correlation effect turns out to be significant in the transitional nuclei, and can reproduce the correct systematics of the two-neutron separation energies [2]. Also the empirical proton-neutron interaction can be evaluated by the so-called δV_{pn} plot, which reflects how the collectivity correlates with the underlying shell structure.

References

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